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ANALYSIS OF TRACKING AND DISPLAYING ERRORS FOR THE  
1.26M INFRARED TELESCOPE

by

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KEY WORDS   Astronomical instrument   Infrared telescope   Error  
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#### ABSTRACT

This article introduces the main errors associated with the 1.26m infrared telescope after it left the factory. It makes use of harmonic analysis methods to separate the various primary error terms associated with the telescope (2m display error, 4m17s short period tracking errors, as well as long period tracking errors, and so on). It discusses error producing factors and calculates theoretical values for errors given rise to by these causes. In conjunction with this, it carries out comparisons with actually measured values, analyses the influences on telescope utilization precision, and describes methods for eliminating the errors as well as actual results.

## I. INTRODUCTION

The "1.26m infrared telescope and its photometry system" was a formal 1981 proposal, going through a number of Ministry of Sciences examined and approved Academia focus projects. In 1982, the Beijing Observatory commissioned the Nanjing astronomical instrument plant to develop parts of the telescope. The telescope in question used relatively fast speeds and relatively low production costs to leave the plant in September 1985. It was installed at Xinglong in Hebei. At the end of the same year, it was put into test observations.

Due to the fact that check out time on the telescope in the plant was relatively short, as a result, errors were comparatively great in test operations. Going through analyses and adjustments, the causes of these errors were precisely determined. Elimination methods were drawn up, and, going through calibrations, the primary errors were very, very greatly reduced or eliminated, increasing the precision of the telescope. This article is an introduction to these analysis and adjustment methods. In conjunction with this, it puts forward tentative ideas for further advances in increasing telescope precision.

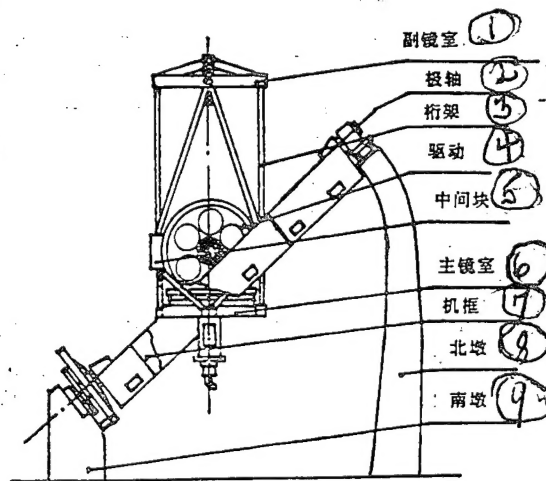


Fig.1 Side-View of the 1.26m Infrared Telescope

Key: (1) Secondary Mirror Chamber (2) Polar Axis (3) Truss  
(4) Drive (5) Intermediate Module (6) Main Mirror Chamber  
(7) Machinery Housing (8) North Pier (9) South Pier

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## II. TELESCOPE ERROR HARMONIC ANALYSIS

Telescope operations are determined by various photoelectromechanical system factors. The position of the light axis is a multiple element function determined by various types of factors:

$$\varphi = F(x, y, \dots, u, \dots)$$

Ideal telescope operations should rotate at uniform speed around the polar axis. One cycle of operation is one sidereal day. When the system structure is imperfect, there must necessarily be a certain error thus giving rise to operational errors associated with the entire telescope, that is:

$$d\varphi = \frac{\partial F}{\partial x} dx + \frac{\partial F}{\partial y} dy + \dots + \frac{\partial F}{\partial u} du + \dots + R$$

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When the various error quantities are very small, the effects of various independent components pile up and that is the overall error associated with the telescope. In order to improve telescope precision, it is necessary to analyze the influence of each component on the overall amount, that is:

$$d\varphi_1 = \frac{\partial F}{\partial x} dx, \quad d\varphi_2 = \frac{\partial F}{\partial y} dy, \dots$$

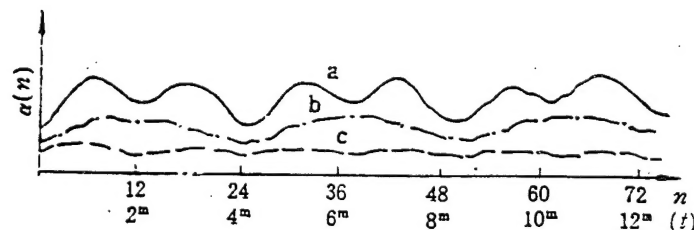


Fig.2 Tracking Display of R.A.

From telescope operational curves, the relatively better methods to analyze out the primary error component constituents are harmonic analysis methods, that is, making use of Fourier transforms to transform measured signals to frequency ranges, separating out different harmonic wave components to search out the sources of errors as well as their frequencies and amplitude values in order to facilitate their respective elimination.

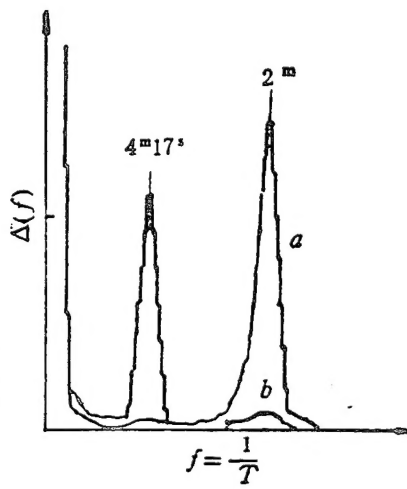


Fig.3  $\alpha$  Data FFT Transform Amplitude Value Components

When the telescope is in ideal constant motion tracking, right ascension  $\alpha$  is a constant. In all cases, any fluctuation measured in  $\alpha$  means that errors exist. As a result, it is possible to make use of--when in constant motion tracking--measurement results for  $\alpha$  to carry out error analysis. For example, adopting  $\Delta t = 10s$ ,  $N \geq 100$ , measurements are obtained for a set of  $\alpha(n)$  data like Fig.2(a). From the Fig., it is possible to see that cyclical fluctuations exist in  $\alpha(n)$  values.

Making use of Beijing Astronomical Observatory's VAX computer Starlink software to carry out FFT transforms on data, see Fig.3(a). It is possible to see that data in the frequency domain possess two amplitude peaks. Corresponding time domain cycles are, respectively, around 2m and 4m. The explanation is that there are two periodic error terms.

Going through empirical measurements, the readings displayed for  $\alpha$  have a p-p that is approximately 7". The cycles are display errors associated with 2m. During tracking, star images in the viewing field have p-p that are approximately 6". Periods are roughly shifts associated with 4m. Analyses indicate that they are, respectively, caused by inductosyn equipment display system errors and auxiliary worm system errors.

### III. CAUSATIVE FACTORS AND ELIMINATION OF 2m DISPLAY ERRORS

Angle measuring systems on right ascension axes are circular induction synchronizers. The operating principle is: assuming that  $E_s$  and  $E_c$  are, respectively, electrical induction potentials associated with stator sine and cosine winding, then,

$$E_s = -K \sin \theta_{elec} \cos \theta_{mech}, \quad E_c = K \cos \theta_{elec} \sin \theta_{mech}$$

In this,  $\theta_{elec}$  is the electrical angle.  $\theta_{mech}$  is the mechanical angle associated with relative displacements between stator and rotor.  $K$  is the electrical induction potential amplitude value.

The overall electrical induction potential is the superposition of the two sine and cosine phase electrical induction potentials, that is, /368

$$E = E_s + E_c = K \sin(\theta_{mech} - \theta_{elec}).$$

When  $\theta_{mech} = \theta_{elec}$ , as far as  $E = 0$  is concerned, it is the objective of going through  $\theta_{elec}$  in order to arrive at measurements for the mechanical angle  $\theta_{mech}$ .

If the two phase windings are not symmetrical, it will then give rise to system error. Assume that  $E_s$  is  $s$  times larger than  $E_c$ . An error angle  $\Delta\theta$  is given rise to, that is, when  $\theta_{mech} = \theta_{elec}$

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+  $\Delta\theta$ , only then is it possible to make  $E = 0$ . The relationship through which  $\Delta\theta$  and  $\theta_{elec}$  are derived is:

$$\Delta\theta = \frac{\varepsilon}{2} \sin 2\theta_{elec}$$

As is shown in Fig.4,  $\Delta\theta$  and  $\varepsilon$  form a direct proportion. Cycles are half the electrical angle cycles. The circular induction synchronizers used in 1.2m infrared telescopes are 720 polar. The electrical angle cycle is 4m. 2m is just the cycle associated with the error angle  $\Delta\theta \propto 4c$

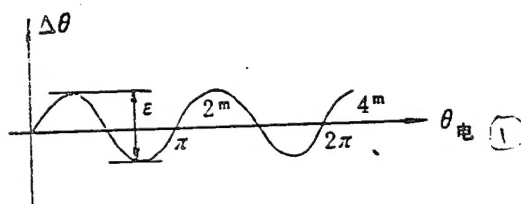


Fig.4 The Error of Inductosyn

Key: (1) elec

As far as eliminating the asymmetry associated with the two phase windings is concerned, it is necessary to carry out a combination of test measurements and adjustments with regard to fine induction synchronizer errors (omitted from this). Going through adjustments, 2m error p-p are already reduced to around 2".

2m errors are system errors and should be calculated from a synthesis of errors associated with induction synthesizers themselves ( $\Delta\varepsilon_1 = \pm 1''$ ) and errors associated with numerical display systems themselves  $\Delta\varepsilon = \pm \sqrt{\Delta\varepsilon_1^2 + \Delta\varepsilon_2^2} = \pm 1.4''$

, that is, approximately p-p 2". It is possible to see that, after adjustments,  $\Delta\varepsilon$  is already within a permissible range.

#### IV. PRODUCTION CAUSES AND ELIMINATION OF 4m17s SHORT PERIOD TRACKING ERRORS

When the telescope in question operates, the components associated with a cycle which is 4m17s are only worm gear auxiliary systems. As a result, 4m17s errors must be produced by these. Going through checks, most of the errors were caused by worm shaft eccentricities. The originally designed worm shaft assemblies were composed of a combination of worm shaft sleeves and worm shaft axle sets used to distribute 180° symmetrical dual key drive as seen in Fig.5. The precision of the 180° symmetrical nature of key grooves exceeds tolerances with the result that dual keys will be off center from the tops of worm shaft sleeves. Going through empirical measurements, worm shaft sleeve key groove ends move up and down radially 0.06. The other end is 0.02. This type of radial up and down movement causes the center distances between worm gears and worm shafts to periodically become larger and smaller thereby giving rise to non-uniformities of worm gear rotation with speeds changing to be faster and slower. The amounts of change associated with rotations are then the radial up and down movements. Through gear meshing, they turn into changing tangential momentums:

$$\Delta r = \Delta r \cdot \tan \theta$$

Converted into angles, they are then 4m17s periodic amounts of right ascension variation:

$$\Delta \alpha = \Delta r / R \cdot 206265'' \approx 8''$$

In the equations,  $\Delta r$  is the amount of radial up and down movement.  $\theta$  is the gear tooth form angle.  $R$  is the worm gear pitch circle radius.

Actually measured 4m17s error p-p are 7", quite close to calculated values.

In order to eliminate this error term, option is made for the use of methods associated with the removal of one key, correcting the degree of concentricity associated with worm shaft keys and worm shaft axles. In conjunction with this, worm shaft edge repairs are carried out, thereby taking worm shaft sleeve eccentricities and dropping them to 0.01 at one end and 0.003 at the other end--approximately a 6 fold reduction compared to the original. The result is to make 4m17s errors given rise to by eccentricities shrink a corresponding 6 fold (approximately 1."0), reaching the predetermined target. /369

At the present time, remaining 4m17s errors are composed of three component quantities: worm gear tooth form error 1."2, worm shaft eccentricity 1."0, and optical code panel error 1."0. Vectors associated with the three and calculated values are:

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$$\varepsilon = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2} \approx 1''.8$$

Actually measured values are 1.''5.

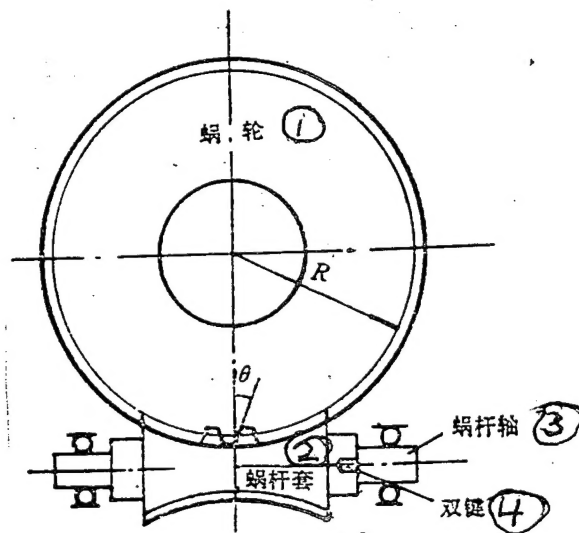


Fig.5 Worm System

Key: (1) Worm Geat (2) Worm Shaft Sleeve (3) Worm Shaft Axle  
 (4) Dual Key

## V. ELIMINATION OF THE CAUSES OF LONG PERIOD TRACKING ERROR DRIFT

Long period telescope errors are primarily constituted by display errors, long period rotation errors, and long period mechanical deformation errors. Among these errors there are included two types of constituents--repetitive errors and nonrepetitive errors. Repetitive errors are repeating functions associated with spacial telescope displacements. Patterns can be found to apply to and correct them. Nonrepetitive errors must be eliminated.

During observations, it was discovered that right ascension  $\alpha$  shows nonrepetitive, long period drift. Going through analyses and checks, it was discovered that, following along with the effects of long term temperature changes and moisture, the fastening of grating code panel verniers loosens up, giving rise to light pulse errors and creating cumulative errors produced in association with  $\alpha$ . Besides that, as far as circular induction synchronizer axle sleeves are concerned, after leaving the factory, they go through grinding, and gaps are relatively large. During tracking, from beginning to end, there is a wriggling downward slide, which goes through long period integration and creates increases in  $\alpha$  readings associated with a direct proportion with time.

Aimed at these phenomena--going through the adoption of appropriate measures--axle sleeve gaps were eliminated, and light code panels were reconditioned, thereby eliminating drift errors. At the present time, the status of long period errors is as shown in Fig.6.

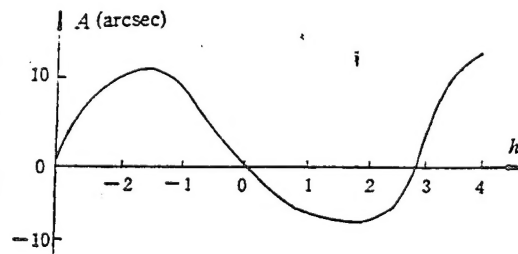


Fig.6 The display error with long time scale

## VI. TELESCOPE TECHNICAL PERFORMANCE AND OUTLOOK AT THE PRESENT TIME

Going through multiple iterations of adjustments and calibrations, primary telescope errors have very, very greatly diminished. As far as calibration results are concerned, see Fig.2(b,c) and Fig.3(b). Evaluations were gone through at the end of 1988. Indices associated with various test measurement items were as follows:

1. 80% of light energy associated with star images concentrated within 1."6.
2. directional precision  $\Delta\alpha = 14.",  $\Delta\delta = 21."rms$$
3. 4m17s error p-p is 1."5.
4. 2m error p-p is 2". /370.
5. long period tracking errors are 1."5/30m.

At the present time, as far as 2m errors are concerned, there still remains approximately 2". However, it shows errors not influencing tracking. Only directional readings are influenced. In comparison to the directional influences of such factors as deformations, it can be ignored. With regard to 4m17s errors, there still remains approximately 1."5. Due to the installation in front of detectors of Fabuli (phonetic) lenses, it is possible to take a number of deviated light foci and put them onto detectors. So long as star images fall, from beginning to end, within detector diaphragms, the influence of this error term on observations is also not great. At the present time, as far as increasing telescope performance is concerned, efforts should be primarily in improving such areas as directional precision and wave chopping performance. The main things are to improve secondary mirror structures, increase the installation rigidity of such mechanical systems as worm shaft frames and eliminate gaps, as well as opting for the use of computer calibration of directional errors, and so on. It is estimated that, after completing these operations, the tracking precision of the telescope in question can improve further, and directional precision over the whole sky can also be controlled within 5"-10".

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